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REVIEW OF INFLATABLE ~~RIGIDIZED~~ SOLAR ENERGY CONCENTRATOR TECHNOLOGY

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REVIEW OF INFLATABLE-RIGIDIZED SOLAR ENERGY CONCENTRATOR TECHNOLOGY

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ABSTRACT

Inflatable-rigidized solar energy concentrator technology has been reviewed with regard to such factors as basic concept, paraboloidal membrane fabrication, rigidizing methods and materials, calorimetric efficiency data, masses, and packaged volumes. A concentrator rigidized at atmospheric pressure has been shown to be sufficiently accurate (efficiency 0.81) for Rankine Cycle conversion systems (operating temperature of 1060° K). Concentrators have been fabricated in a simulated space environment but efficiencies of only about 0.50 have been measured. Unit masses for all concentrators rigidized in a simulated space environment fall in the range of 1.22 to 3.78 kg/m^2 which is comparable to masses obtained on other types of expandable concentrators. The packaged volume of a 1.52-meter-diameter concentrator has been shown to be about 0.06 m^3 and an estimate of 1.40 m^3 has been made for a 15.24-meter concentrator.

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INTRODUCTION

Studies of space power systems utilizing solar energy have shown that one-piece solar energy concentrators, because of their relatively good optics, will have the smallest size for a given power level[1]. However, power requirements could dictate a concentrator diameter larger than the diameter of any launch vehicles under consideration. One obvious solution to this problem is the expandable concentrator that can be compactly packaged for launch and then deployed for use in space. Much effort has gone into the development of such expandable types as the flat foldable Fresnel, the petalous, and the inflatable-rigidized concentrators. Previous studies[2] of the capabilities of these expandable concentrators have shown that highly accurate surface geometry has not been attained but surface geometries capable of efficiently generating operating temperatures up to 1200° K are practical. Such temperatures are required for dynamic conversion systems utilizing turbine-generator combinations.

Of the three expandable types mentioned, the inflatable-rigidized concentrator presents the most formidable problem, which, in brief, is the fabrication by remote control of an optical device. A review of the results of numerous technology programs in this area is presented in this paper.

Paraboloidal membranes have been fabricated and rigidized at atmospheric pressure as well as in vacuum chambers to simulate space conditions. Information on these concentrators such as fabrication techniques, calorimetric

L-4991

efficiencies, masses, and packaged volumes are presented and discussed to indicate the achievements to date.

Basic Concept

There are two general approaches to the formation of an inflatable-rigidized concentrator in space. Sketches of these concepts are shown in figure 1. Figure 1(a) shows the balloon concept[3] in which a clear plastic envelope is attached to the preformed aluminized paraboloid to form a balloon with a diameter twice that of the final concentrator. In space, the balloon is inflated, the paraboloid rigidized, and then the clear plastic is detached from the paraboloid and discarded. The second concept[4], figure 1(b), is a lenticular body composed of the aluminized paraboloid and a clear plastic cover. An inflatable torus attached to the paraboloid-cover juncture maintains the correct diameter and shape. The same sequence of events used to fabricate the balloon concept is also used for this type.

The first problem to be encountered is the fabrication of the reflecting paraboloid from a sheet of thin, 0.025- to 0.125-millimeter-thick aluminized plastic. As indicated in figure 1(a), flat gores of the plastic can be used[3]. The gores are cut and then joined together on a mold which differs from the desired paraboloid in such a fashion that inflation pressure gives the desired paraboloidal shape. Another method[5] has been used with success and is known as the stretch-relaxation process. A membrane in a fixture is deformed to a curvature slightly greater than the final value desired by the application of a differential pressure. The resulting shape is an oblate ellipsoid; however, upon a slight relaxation of the differential pressure, the desired paraboloidal shape may be obtained.

It may be noted in figure 1(b) that the clear plastic cover is a mosaic composed of hexagonal elements. The mosaic, which also may be used for the reflective paraboloid[5], is an alternate solution to the fabrication of large paraboloids by the use of gores as shown in figure 1(a). The use of fabrication methods such as these is dictated by the fact that thin plastics are available only in rolls of limited width.

GROUND TEST CONCENTRATORS

Fabrication

Several inflated membranes have been rigidized on the ground at atmospheric pressure. These models are important because they give an indication of what can be done under closely controlled conditions with rigidizing materials chosen for favorable characteristics. Table 1 lists four ground rigidized concentrators with pertinent fabrication information. Sketches of each type are shown in figure 2, and a brief discussion of each of the processes follows.

Figure 2(a) shows the method used to rigidize a 13.87-meter-diameter concentrator[6]. The aluminized plastic skin was inflated and first sprayed with a thin layer of epoxy to prevent show-through of the succeeding layers of polyurethane foam. The foam was applied in three layers with the first layer being relatively dense at 160 kg/m^3, and the next two layers having a density of only 40 kg/m^3. The final layer was a thin epoxy shell coat. A metal backup structure was then attached with foam to support the structure during ground tests on a solar tracker.

Two models have been rigidized by the method shown in figure 2(b). One model, 3.05 m in diameter[6], was fabricated by pouring several layers of polyurethane foam over the inflated aluminized plastic. The second model, 0.51 m in diameter[5], was rigidized by pouring one layer of foam over the skin.

Another method of rigidization is shown in figure 2(c)[7]. A thin layer of epoxy was first applied to the 1.52-meter-diameter aluminized skin and then cured. Additional structural strength was obtained by applying a 3-ply laminate of fiber-glass cloth and epoxy.

Efficiency

The four models described in the preceding section have all been tested to determine their efficiency. Three of the models were tested with cold calorimeters which are essentially heat absorbers which operate at near ambient temperatures thus limiting reradiation. The 0.51-meter model, however, was compared to a 0.15-meter-diameter standard mirror to obtain the product of specular reflectance and imaging efficiency[5] which is comparable to calorimetric efficiency.

Figure 3 shows the efficiency as a function of aperture diameter ratio for the four models. The efficiency is based on the unobscured projected area of each concentrator in order to provide a common basis for comparison. The aperture diameter ratio is the ratio of the calorimeter aperture diameter to the concentrator diameter. All of the concentrators had a reflective surface of vacuum-deposited aluminum.

Solar concentrator design points for a Brayton Cycle power system[8] and a Rankine Cycle power system[9] are indicated on the figure to show typical requirements for solar concentrators. None of the concentrators is efficient enough to be used with the Brayton Cycle system; however, the efficiency of the 13.87-meter-diameter model[6] closely approaches the design value for the Rankine Cycle system. The rigidizing method used for this concentrator does not appear to be practical for space use as the structure was built up of successive layers of different materials. The results obtained on this concentrator do show however that the plastic membrane can be fabricated with sufficient accuracy to concentrate the solar rays efficiently for operating temperatures near 1060° K (Rankine Cycle system).

The effect of rigidizing is also shown on this figure. At an aperture ratio of 0.02, the 0.51-meter-diameter concentrator had an efficiency of 0.66 for the shaped membrane alone. After rigidizing, an efficiency of only 0.45 was obtained which is a loss of about 1/3. A polyurethane foam was used and a reflectance loss due to surface irregularities commonly called orange-peel as well as a contour change due to shrinkage of the foam are both possible.

The 1.52-meter-diameter epoxy-fiberglass concentrator[7] is the most efficient of all below an aperture ratio of 0.03. The data shown in figure 3 were obtained by masking the outer 0.1 m of the concentrator radius because measurements showed that an approximately 0.06 loss in reflectance was present over that area.

The 3.05-meter-diameter foam concentrator[6] is the least efficient of all. The maximum efficiency reached is about 0.70 which is essentially the specular reflectance of the surface. This low value of reflectance, compared to a usual value in excess of 0.80 for aluminized polyethylene terephthalate, has been attributed to orange-peel.

SIMULATED SPACE RIGIDIZED CONCENTRATORS

Fabrication

Numerous models varying in diameter from 0.61 to 3.05 m have been inflated and rigidized in vacuum chambers at pressures well below atmospheric. A summary of the concentrators with pertinent characteristics is given in table 2. Although the effects of zero gravity are absent, the rigidization at reduced pressure provides an indication of some of the problems that have been encountered. Sketches of the rigidization methods are shown in figure 4 and descriptions of the various types follow.

Figure 4(a) shows the structure obtained in a demonstration of the mechanically mixed foam method[6]. A mechanical mixer located at the apex of the concentrator mixes the constituents of the polyurethane foam which is then forced between the inflated reflective film and a thin plastic backflap. Models of 0.61-meter diameter have been successfully rigidized in a vacuum but an attempt to fabricate a 13.56-meter-diameter model at atmospheric pressure was unsuccessful[6]. The lack of success was attributed to a poor distribution of foam, from the centrally located mixer, over the relatively large area of the concentrator.

Figure 4(b) shows the epoxy syntactic foam approach[4]. The epoxy plastic is mixed with small hollow phenolic spheres to make the foam which is applied in a thin layer to the reflective membrane. Rigidization occurs upon heating the foam to about 365° K for 24 hours. In early tests, the foam outgassed and bubbled in the vacuum during the application of heat thus resulting in a poor reflective surface. Two thin perforated plastic membranes were added to the back in later tests to allow the gases to escape with less bubbling.

The next sketch, figure 4(c), shows a reinforced laminate of fiber-glass and polyester resin attached to the reflective membrane with a flexible layer of polysulphide to prevent show-through of the fiber-glass fabric[4]. The polysulphide also bonds the polyester to the plastic membrane. The two plastic films on the back act to prevent delamination during curing and as a parting layer to prevent adhesion of adjacent folds of the uncured polyester when packaged. Ultraviolet radiation acts as a catalyst to the resin, and complete rigidization occurred after an exposure of approximately 16 hours.

Figure 4(d) shows a cross section of the predistributed polyurethane foam approach[10]. The polyurethane formulation is spread over the back of the membrane in a thin layer. A thin plastic back cover is used to prevent adhesion of the polyurethane when the membrane is folded. The formulation is activated when heated to a temperature between 350° to 365° K, then a rapid temperature rise to over 420° K due to the exothermic reaction takes place. From the start of foam activation to the end of cure, the process takes only about 30 minutes.

Figure 4(e) shows a cross section of the structure used for the gelatin rigidized concentrators[11]. The aluminized plastic was first sprayed with a flexible layer of epoxy resin and then a nylon sandwich drop thread material fabricated in a paraboloidal shape to fit the inflated membrane was added. The sandwich material was impregnated with a gelatin solution which caused the structure to rigidize upon exposure to a vacuum by evaporation of the solvents from the solution.

Figure 4(f) shows a cross section of the structure of the urethane-rigidized sandwich drop thread material[12]. The construction of this concentrator is similar to that of the gelatin-rigidized sandwich material previously discussed with the exception that a urethane resin is used to impregnate the sandwich instead of gelatin. The structure is rigidized by the introduction of water vapor and amine between the layers of the resin-impregnated sandwich material.

Efficiency

Only three of the concentrators described in the preceding section have been tested in sunlight with a cold calorimeter and the results are shown in figure 5. The efficiency and the ratio of aperture diameter to concentrator diameter are the same as used in figure 3. It is noticed that none of the three closely approaches the efficiencies required for the Brayton and Rankine Cycle systems. The 1.52-meter-diameter concentrators of epoxy syntactic foam and polyester fiber-glass laminate are about the same in calorimetric efficiency and both are slightly higher than the 0.61-meter-diameter concentrator made of predistributed polyurethane foam.

Two reasons for the low efficiencies obtained with the 1.52-meter-diameter models have been identified[4]. First, the shape of the concentrators deviated from a paraboloid. The concentrators were surveyed, and it was found that over half of the reflective area of each had surface slope errors greater than 0.5°. Second, each surface had imperfections that resulted in blurred images such as might be attributed to a large component of diffuse reflectance. In the epoxy model, the imperfections were caused by pockets of entrapped gas that caused small craters and excrescences in the reflective surface. In the polyester model it appeared that the polyester fiber-glass laminate had shrunk slightly thus causing a patternless wrinkling in the polysulphide layer immediately behind the reflective skin.

The 0.61-meter-diameter polyurethane foam model was fabricated primarily to demonstrate that the predistributed foam concept could be successfully carried out in a vacuum. Consequently no stiffening structure was added to hold the shape that was present at the end of the curing period. It should also be noted that models of this size have an abnormally large percentage of surface area with seams that cause distortion in the reflective surface. However, an orange-peel condition was noticed in the reflective surface that would cause an undetermined loss in efficiency.

Several models of the urethane-nylon sandwich material had a good surface appearance at the end of the cure period[12] but developed wrinkles after a short time. These wrinkles were attributed to a residual solvent attack on the flexible layer causing separation of the reflective film.

MASS

The unit masses of the various simulated space rigidized concentrators are listed in table 2. These masses vary from 1.22 to 3.78 kg/m^2 and fall in the same range as those obtained on other expandable concentrators such as the petal concept[2]. The achieved masses are relatively low and might be a cause for the poor quality of the concentrators, as it has been observed by numerous investigators that there is a correlation between mass and optical quality. For example, it has been pointed out[4] that an increase in the thickness of the reflective membrane, and hence increased mass, can minimize show-through due to foam cell pattern and fabric weave. However, the previously mentioned materials problems such as shrinkage, solvent attack, and large seam areas rather than low mass are considered to be the major factors contributing to the relatively low calorimetric efficiency of the concentrators. Ultimately, of course, the final mass will depend on size, rigidizing material, and the maneuvering and pointing accelerations required for the particular space mission involved.

PACKAGED VOLUME

The inflatable-rigidized concept has always appeared attractive because of the possibility of obtaining a compact launch package. In addition, the shape of the package may be varied if required by the available space in the launch vehicle.

A curve of estimated concentrator packaged volume as a function of concentrator diameter[3] is given in figure 6. This curve was based on available material and fabrication techniques prevailing in 1962. The packaged volume varies from 0.03 m^3 for a 1.52-meter-diameter concentrator to about 0.85 m^3 for a 15.24-meter-diameter concentrator.

Packaged volumes of three inflatable structures are also shown in figure 6. The 1.52-meter-diameter concentrator with a volume of about 0.06 m^3 is the epoxy syntactic foam model[4] listed in table 2 and consists of the paraboloid with flexible foam backing, clear plastic cover, and torus. Space in the container was also available for gas bottles and controls.

A 6.10-meter-diameter lenticular test satellite[13] similar to an inflatable concentrator, as shown in figure 1(b), with a lenticular body and inflated torus has been built and packaged. The value of 0.06 m^3 is for the packaged plastic and does not include any rigidizing materials. If a 6.35-millimeter layer of the predistributed polyurethane foam were added to the satellite, it is estimated that the packaged volume would be at least 0.26 m^3.

The 30.48-meter-diameter Echo I satellite[14], which is similar to a 15.24-meter-diameter concentrator utilizing the balloon concept of figure 1(a), had a packaged volume of about 0.17 m^3. If a 6.35-millimeter layer of the predistributed polyurethane foam were added, an estimated volume of 1.40 m^3 would result.

A new curve based on the estimated values has been drawn which is slightly higher than the original prediction[3]. It is realized that this estimated curve is optimistic as no allowance has been made for difficulty in folding the coated plastic film. However, the curve does give an indication of what packaged volumes may be expected.

CONCLUDING REMARKS

A review has been made of the results achieved in the inflatable-rigidized solar concentrator technology program. A brief summary of the various areas of accomplishment follows.

Reflective plastic membranes can be fabricated into rigidized paraboloids with sufficient accuracy to concentrate solar energy efficiently (efficiency 0.81) for heat receivers operating near 1060° K.

Available data on concentrators rigidized in vacuum chambers to simulate a space environment indicate that efficiencies of only about 0.50 have been achieved at aperture ratios suitable for 1060° K operation.

Unit masses for the concentrators rigidized in vacuum chambers fall in the range of 1.22 to 3.78 kg/m^2 which is comparable to the masses obtained on other types of expandable concentrators.

The packaged volume of a 1.52-meter-diameter concentrator has been shown to be about 0.06 m^3. Volumes for larger concentrators with the rigidizing material applied are unavailable but it is estimated that a 15.24-meter-diameter concentrator might be packaged in a volume as low as about 1.40 m^3.

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TABLE 1.- GROUND RIGIDIZED CONCENTRATORS

Diameter, m	Rim angle,* deg	Membrane	Rigidizing material	Membrane thickness, mm	Membrane construction	Unit mass, kg/m^2	Reference
13.87	60	Polyethelene terephthalate	Epoxy + polyurethane foam	0.025	Gores	----	6
3.05	60	Polyethelene terephthalate	Polyurethane foam	.025	Gores	----	6
.51	45	Polyethelene terephthalate	Polyurethane foam	.051	One piece (stretch-relaxation)	2.44	5
1.52	60	Polyethelene terephthalate	Epoxy fiber glass	.025	Gores	2.42	7

*Angle formed by optical axis and line from focus to rim.

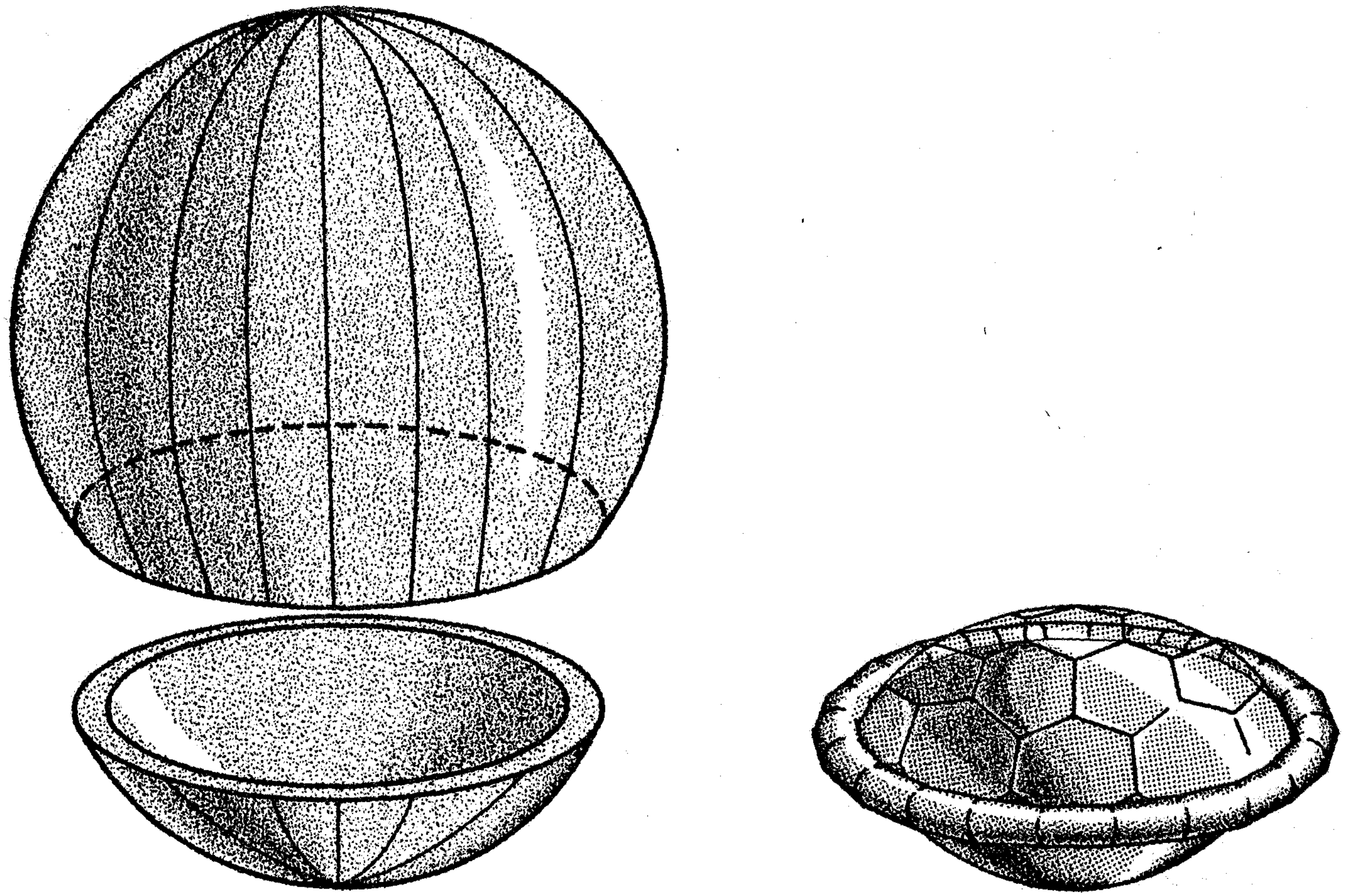
TABLE 2.- SIMULATED SPACE RIGIDIZED CONCENTRATORS

Diameter, m	Rim angle,* deg	Membrane	Rigidizing material	Vacuum chamber press, N/m^2	Rigidizing method	Unit mass, kg/m^2	Reference
0.61	60	Polyethylene terephthalate	Polyurethane foam	1870	Mechanical mixing	------------	6
1.52	45	Polyethylene terephthalate	Epoxy syntactic foam	670	Thermal	2.05	4
1.52	45	Polyethylene terephthalate	Polyester fiber glass	670	UV	1.95	4
.61	60	Polyimide	Polyurethane foam	13.3	Thermal	1.27	10
**.61	60	Polyethylene terephthalate	Gelatin nylon	6.1×10^{-3}	Vacuum	3.12	11
.61	60	Polyethylene terephthalate	Urethane nylon	6.5×10^{-2}	H_2O-amine	***1.22-3.78	12
3.05	60	Polyethylene terephthalate	Urethane nylon	----------	H_2O-amine	------------	12

*Angle formed by optical axis and line from focus to rim.

**Typical of several models.

***Range of 24 models.



(a) BALLOON

(b) LENTICULAR

Figure 1.- Inflatable-rigidized concentrator basic concepts.

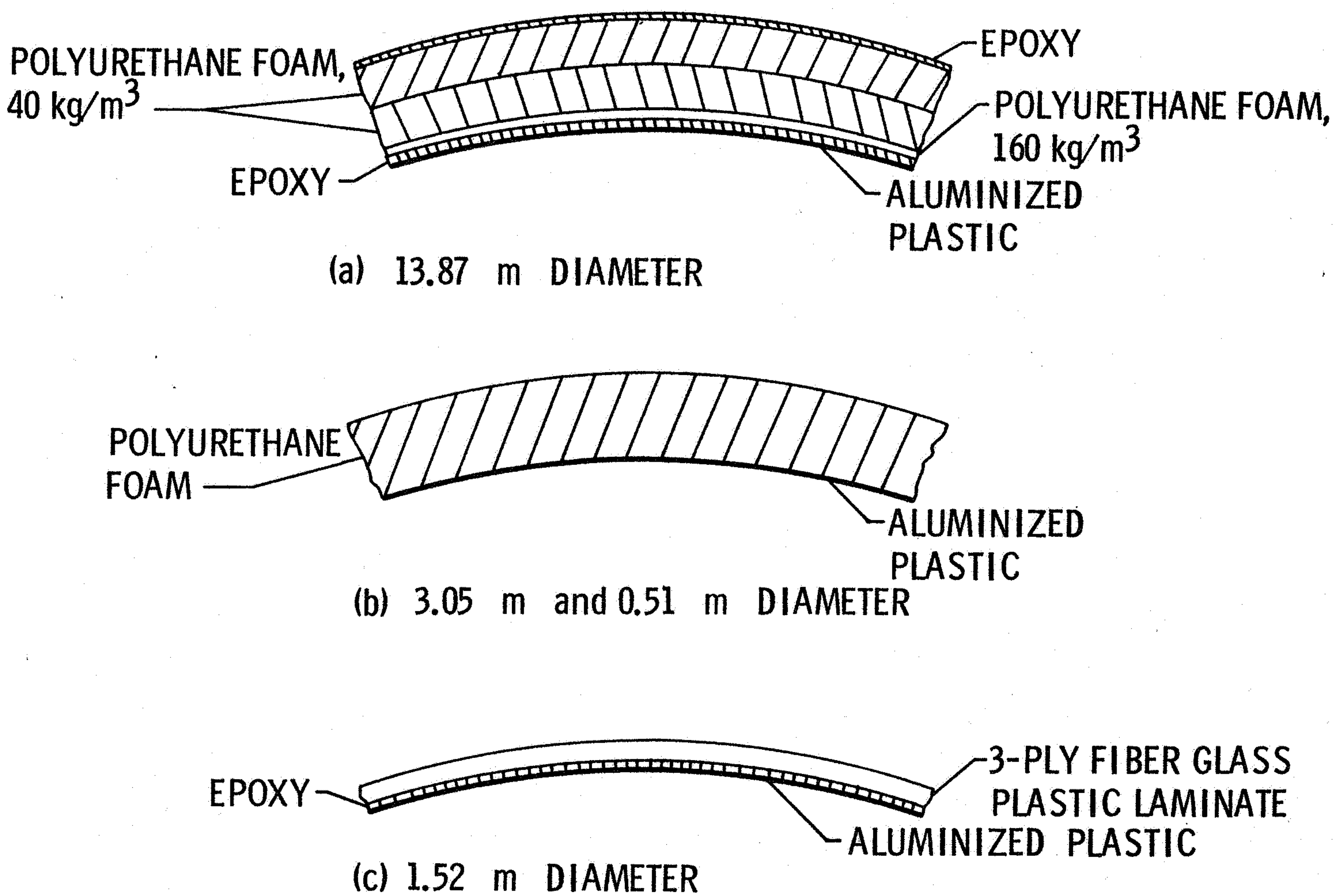


Figure 2.- Cross sections of ground test concentrators.

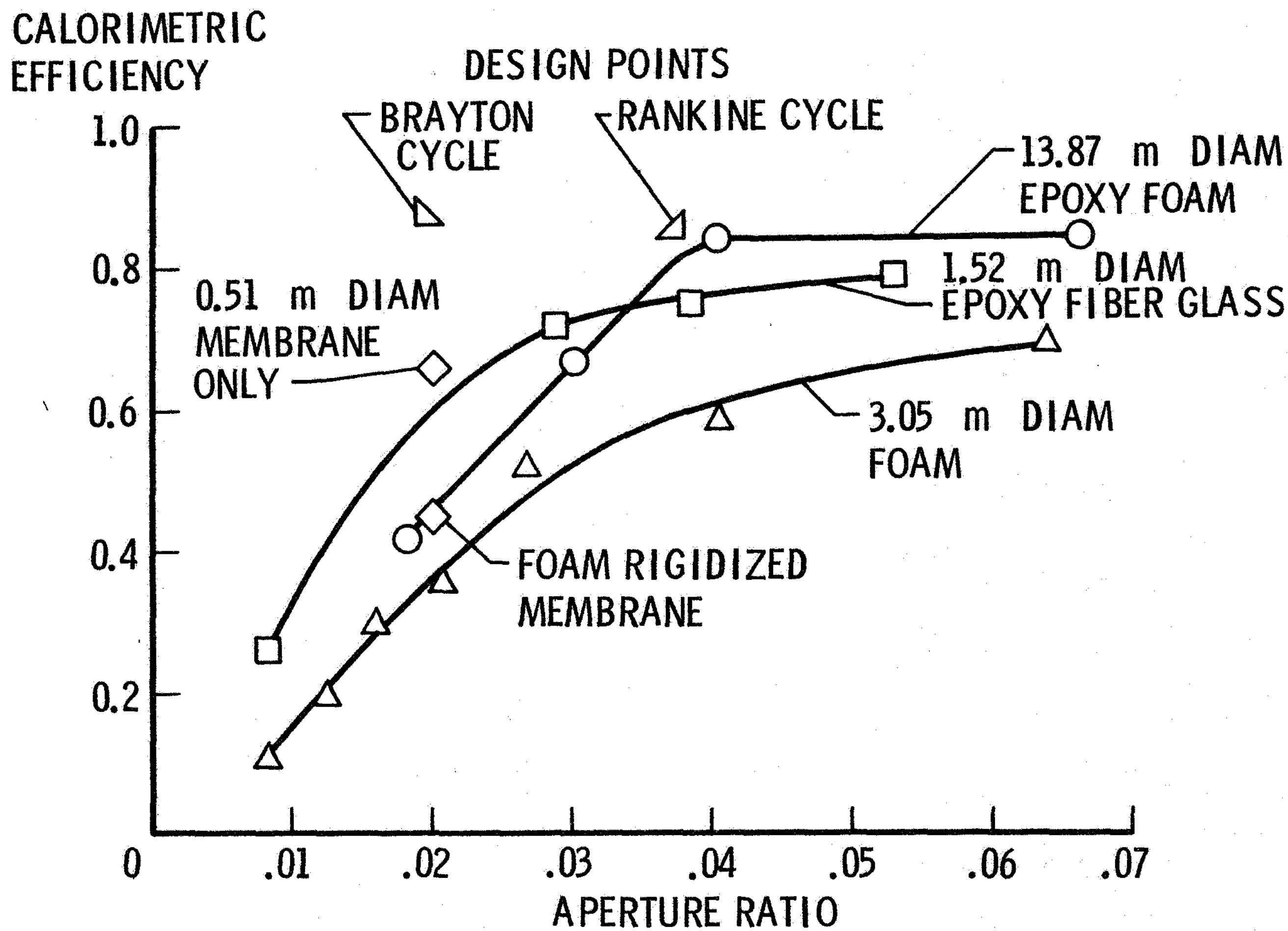


Figure 3.- Calorimetric efficiency of ground test concentrators.

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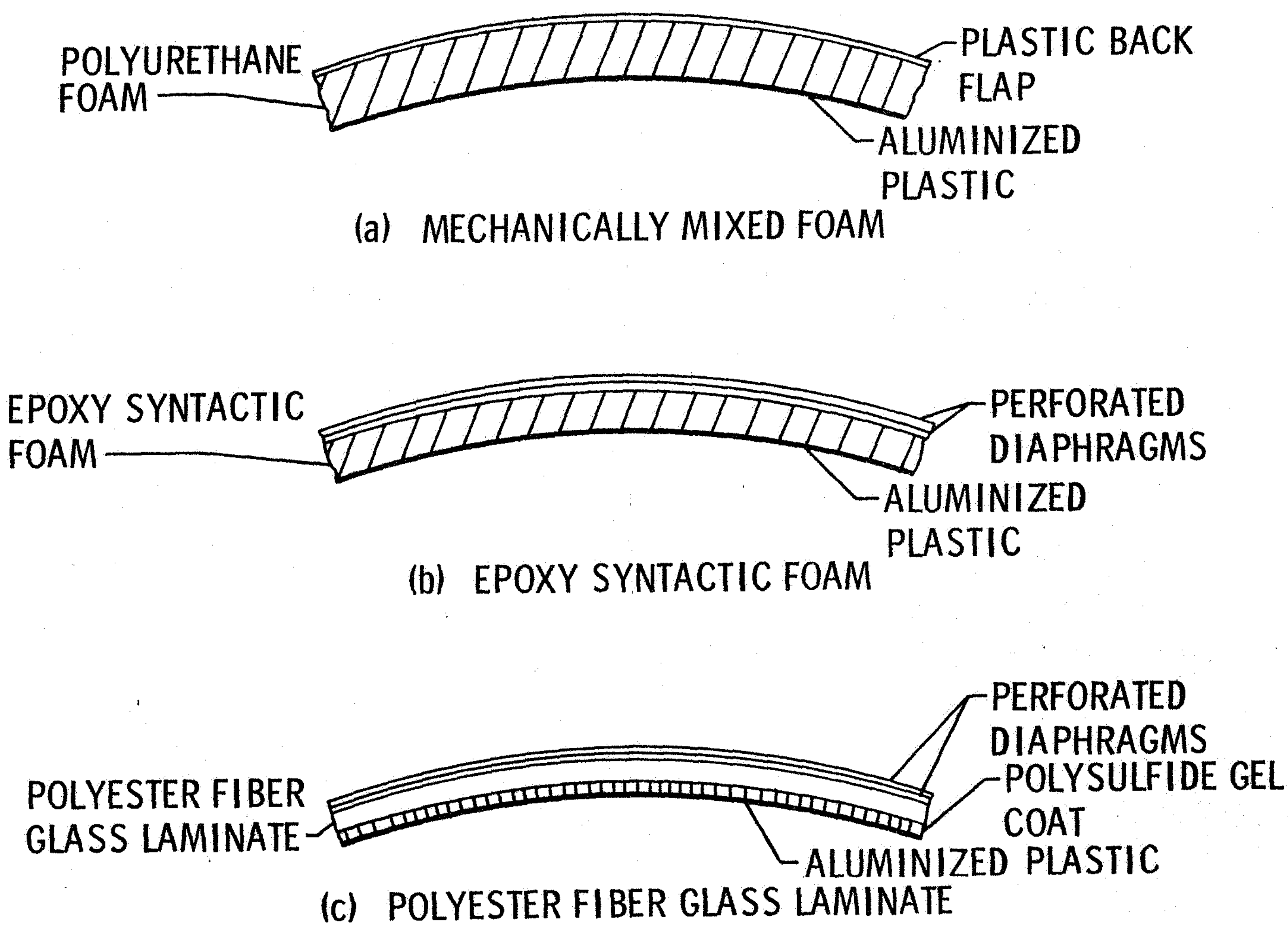

Figure 4.- Cross sections of simulated space rigidized concentrators.

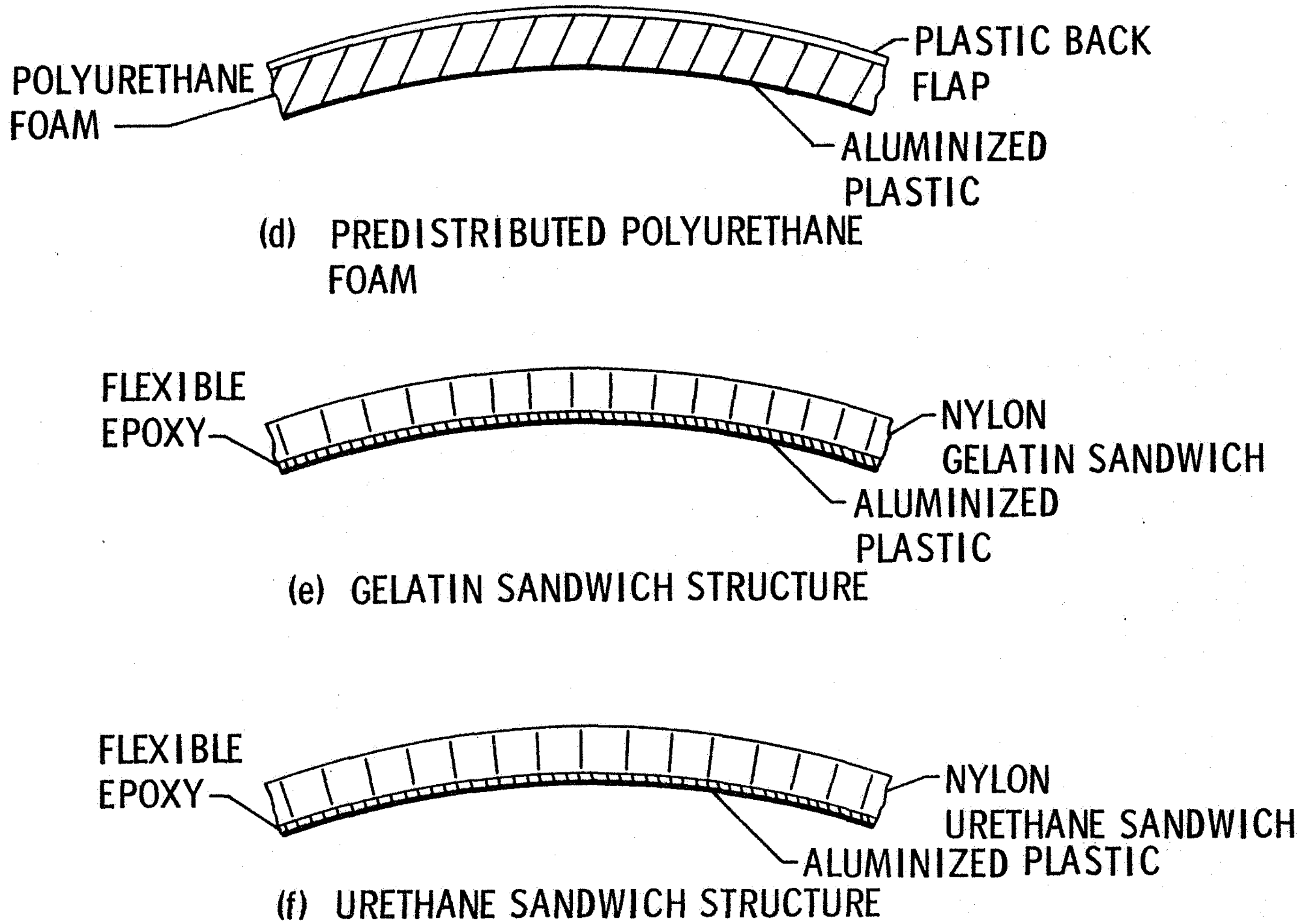

Figure 4.- Concluded.

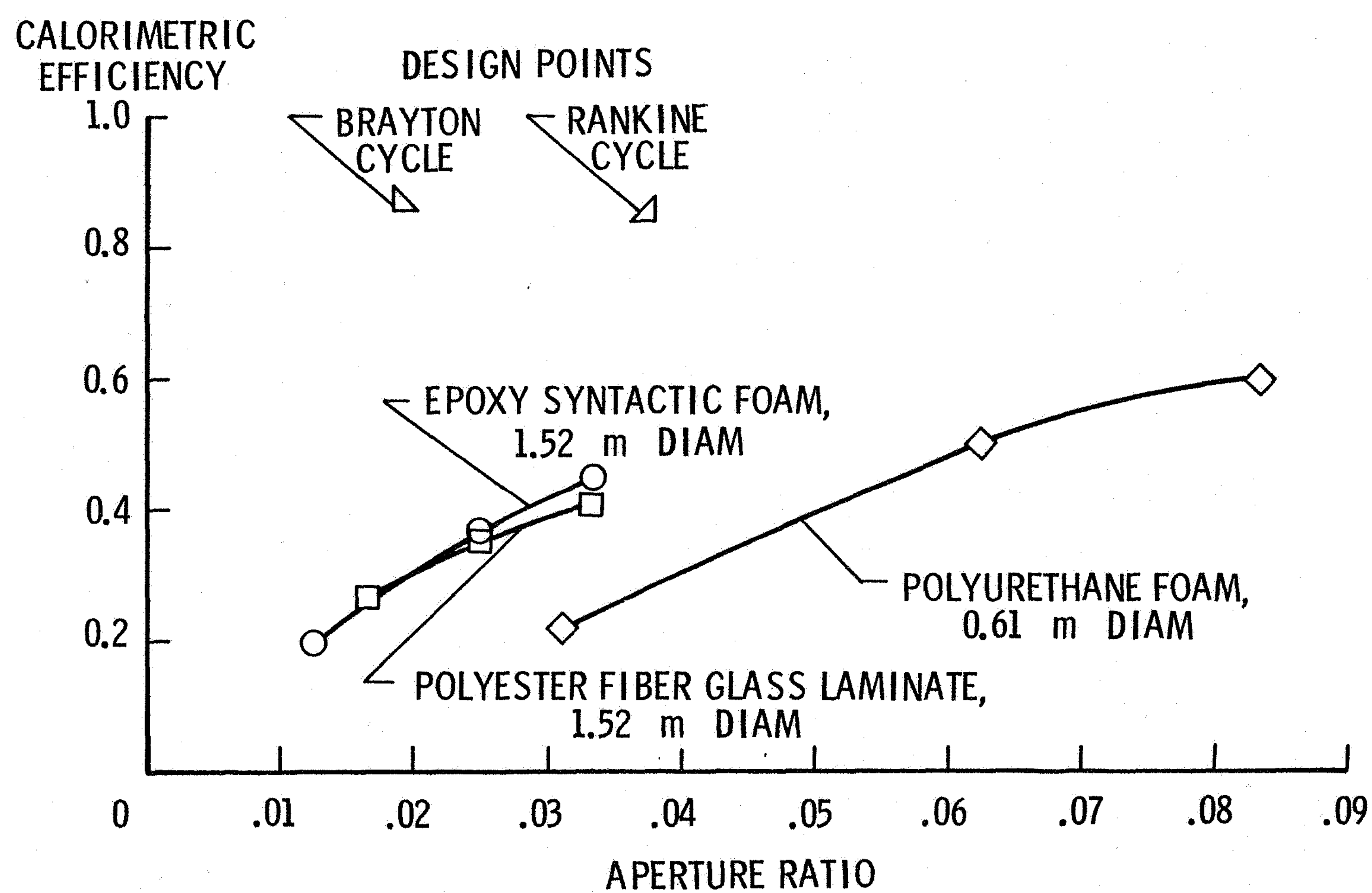

Figure 5.- Calorimetric efficiency of simulated space rigidized concentrators.

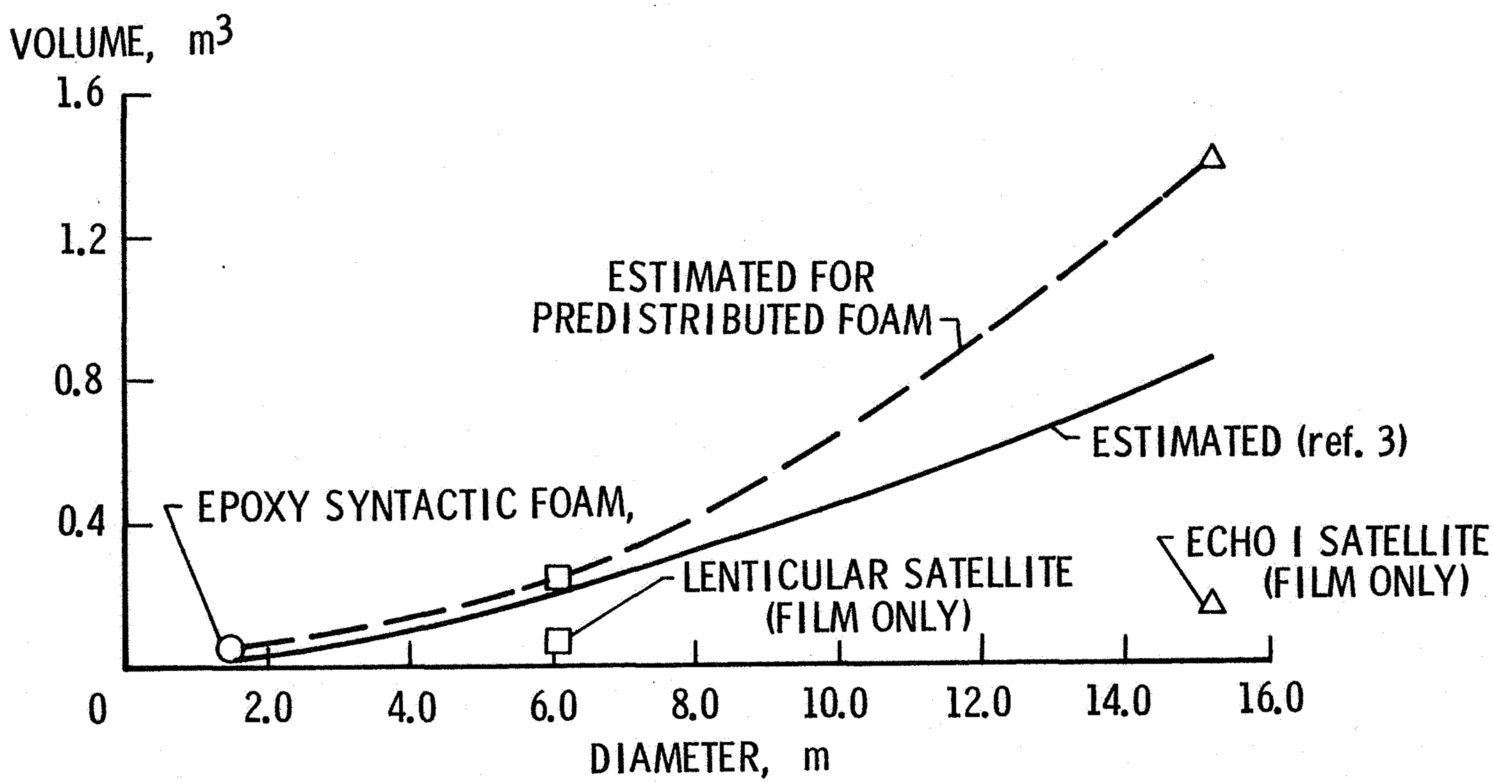

Figure 6.- Concentrator packaged volume.

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28. MISSILES AND SATELLITE CARRIERS: weapons; sounding rockets; satellite launchers.
29. NAVIGATION AND NAVIGATION EQUIPMENT
30. PHYSICS, ATOMIC AND MOLECULAR: structures; spectroscopy; periodic system.
31. PHYSICS, NUCLEAR AND PARTICLE: radiation; nuclear reactions; structures; force fields.
32. PHYSICS, SOLID STATE: cryogenics, crystallography; semiconductors; theories of elasticity, plasticity.
33. PHYSICS, THEORETICAL: classical mechanics other than fluid mechanics; magnetism; optics; acoustics; wave and quantum mechanics.
34. PILOTING: preflight and flight routines; rescue operations.
35. POWER SOURCES, SUPPLEMENTARY: auxiliary sources; batteries; solar and nuclear generators.
36. PROPELLANTS: characteristics; handling.
37. PROPULSION SYSTEM ELEMENTS: injectors; nozzles; heat exchangers; pumps.
38. PROPULSION SYSTEMS, AIR-JET: turbojets; ramjets; propeller systems. Includes these types using nuclear heat sources.
39. PROPULSION SYSTEMS, LIQUID-FUEL ROCKETS
40. PROPULSION SYSTEMS, SOLID-FUEL ROCKETS
41. PROPULSION SYSTEMS, ELECTRIC: ion jets; plasma jets.
42. PROPULSION SYSTEMS, NUCLEAR: fission or fusion systems using non-ambient working fluids.
43. PROPULSION SYSTEMS, OTHER: systems not assignable to other categories, e. g. solar radiation.
44. PROPULSION SYSTEMS, THEORY: analyses not assignable to listed categories; factors such as combustion parameters, thrust, efficiency.
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46. SPACE MECHANICS: orbital calculations and observations.
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52. STRUCTURES: design criteria; component selection.
53. VEHICLE PERFORMANCE: specific flights; observed performance; history.

(Numbers above 53 not assigned.)

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